UNITED STATES PATENT APPLICATION

OF

GIDEON P. STEIN AND AMNON SHASHUA

FOR

SYSTEM AND METHOD FOR GENERATING A MODEL OF THE PATH OF A ROADWAY FROM AN

IMAGE RECORDED BY A CAMERA

1 ## INCORPORATION BY REFERENCE

2 U. S. Patent Application Serial No. 09/723,754, filed on November 26, 2000, in the names

3 of Gideon P. Stein, Ofer Mano And Amnon Shashua, and entitled "System And Method For

4 Estimating Ego-Motion Of A Moving Vehicle Using Successive Images Recorded Along The

5 Vehicle's Path Of Motion" (hereinafter referred to as "the Stein I patent application"), assigned to

6 the assignee of the present application, incorporated herein by reference.

7 U. S. Patent Application Serial No. 09/723,755, filed on November 26, 2000, in the names

8 of Gideon P. Stein And Amnon Shashua, and entitled "System And Method For Generating A Model

9 Of The Path Of A Roadway From A Sequence Of Images Recorded By A Camera Mounted On A

10 Moving Vehicle" (hereinafter referred to as "the Stein II patent application") assigned to the assignee

11 of the present application, incorporated herein by reference.

12 ## FIELD OF THE INVENTION

13 The invention relates generally to the field of systems and methods for generating an estimate

14 as to the structure of a roadway from a vehicle and more specifically to systems and methods for

15 generating an estimate using an image recorded from the vehicle.

16 ## BACKGROUND OF THE INVENTION

17 Accurate estimation of the structure of a roadway ahead of a vehicle is an important

18 component in autonomous driving and computer vision-based driving assistance. Using computer

19 vision techniques to provide assistance while driving, instead of mechanical sensors, allows for the

20 use of the information that is recorded for use in estimating vehicle movement to also be used in

21 estimating ego-motion identifying lanes and the like, without the need for calibration between

22 sensors as would be necessary with mechanical sensors. This reduces cost and maintenance.

1   There are several problems in determining the structure of a roadway. Typically, roads have

2   few feature points, if any. The most obvious features in a road, such as lane markings, are often

3   difficult to detect and have a generally linear structure, whereas background image structures, such

4   as those associated with other vehicles, buildings, trees, and the like, will typically have many

5   feature points. This will make image- or optical-flow-based estimation difficult in practice. In

6   addition, typically images that are recorded for roadway structure estimation will contain a large

7   amount of "outlier" information that is either not useful in estimating roadway structure, or that may

8   result in poor estimation. For example, in estimating of roadway structure, images of objects such

9   as other vehicles will contribute false information for the road structure estimation. In addition,

10   conditions that degrade image quality, such as raindrops and glare, will also make accurate road

11   structure estimation difficult.

SUMMARY OF THE INVENTION

13   The invention provides new and improved systems and methods for generating an estimate

14   of the structure of a roadway using an image recorded from the vehicle.

15   In brief summary, the invention provides a road skeleton estimation system for generating

16   an estimate as to a skeleton of at least a portion of a roadway ahead of a vehicle. The road skeleton

17   estimation system includes an image receiver and a processor. The image receiver is configured to

18   receive image information relating to at least one image recorded ahead of the vehicle. The

19   processor is configured to process the image information received by the image receiver to generate

20   an estimate of the skeleton of at least a portion of the roadway ahead of the vehicle.

BRIEF DESCRIPTION OF THE DRAWINGS

This invention is pointed out with particularity in the appended claims. The above and further advantages of this invention may be better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:

FIG. 1 schematically depicts a vehicle moving on a roadway and including a roadway skeleton estimation constructed in accordance with the invention;

FIG. 2 depicts a graph that schematically depicts a model of a roadway skeleton, useful in understanding one embodiment of the invention;

FIG. 3 schematically depicts an image of a portion of a roadway, useful in understanding outputs performed by the roadway skeleton estimation system; and

FIGS. 4 and 5 depict flow charts depicting operations performed by the roadway skeleton estimation system in estimating the skeleton of the roadway, FIG. 4 depicting operations in connection with a model in which the roadway is modeled as a circular arc and FIG. 5 depicting operations in connection with a model in which the roadway is modeled as a parabolic arc.

DETAILED DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT

FIG. 1 schematically depicts a vehicle 10 moving on a roadway 11 and including a roadway skeleton estimation system 12 constructed in accordance with the invention. The vehicle 10 may be any kind of vehicle 10 that may move on the roadway 11, including, but not limited to automobiles, trucks, buses and the like. The roadway skeleton estimation system 12 includes a camera 13 and a processor 14. The camera 13 is mounted on the vehicle 10 and is preferably pointed in a forward direction, that is, in the direction in which the vehicle would normally move, to record successive images as the vehicle moves over the roadway. Preferably as the camera 13 records each image, it will provide the image to the processor 14. The processor 14, in turn, will process

1   information that it obtains from the successive images, possibly along with other information, such

2   as information from the vehicle's speedometer (not separately shown) to estimate a roadway skeleton

3   representing a portion of the roadway 11 ahead of the vehicle 10. The processor 14 may also be

4   mounted in or on the vehicle 11 and may form part thereof. The roadway skeleton estimates

5   generated by the processor 14 may be used for a number of things, including, but not limited to

6   autonomous driving by the vehicle, providing assistance in collision avoidance, and the like.

7   Operations performed by the processor 14 in estimating the roadway skeleton will be described in

8   connection with the flow chart depicted in FIG. 3.

9   Before proceeding further, it would be helpful to provide some background to the operations

10   performed by the processor 14 in estimating the skeleton of the roadway 11. This background will

11   be described in connection with FIG. 2. Generally, the roadway is modeled as a circular arc parallel

12   to the XZ plane in three-dimensional space. The X (horizontal) and Y (vertical) axes of three-

13   dimensional space correspond to the "x" and "y" axes of the image plane of the images recorded by

14   the camera 14, and the Z axis is orthogonal to the image plane. Preferably, the image plane will be

15   the plane of the image after the image has been rectified to provide that the Z axis is parallel to the

16   plane o the roadway 11; the Stein I patent application describes a methodology for rectifying the

17   images to provide that the image plane will have a suitable orientation.

18   As noted above, the roadway is modeled as a circular arc, and, with reference to FIG. 2, that

19   FIG. circular arc in the XZ plane representing the roadway, which will be referred to as the

20   roadway's skeleton, is identified by reference numeral S. Two lane markings 20L and 20R are also

21   shown as dashed lines on opposite sides of the skeleton S. The distances R1 and R2 between the

22   lane markings 20L and 20R and the skeleton S may be the same, or they may differ. The skeleton

23   S of the roadway is modeled as an arc extending from the vehicle 10, or more specifically from the

24   image plane of the camera 14, which is deemed to be at point P=(0,0), the origin of the XZ plane.

25   The center of the circular arc need not be along the X axis, and, indeed will generally be at an angle

26   α thereto. The circular arc is parameterized by three components, namely

1   (i) the coordinates of the center (Xc, Yc) of the circular arc (the coordinates of the center will

2   also be referred to as coordinates (a,b));

3   (ii) the angle α and the inverse of the radius 1/R, and

4   (iii) for two locations Z1 and Z2 along the Z axis, values X1 and X2. In one embodiment,

5   Z1 and Z2 are three meters and thirty meters, respectively.

6   For item (iii), value X1 represents the horizontal distance between the Z axis, specifically the point

7   with coordinates (0,Z1), and the point on skeleton S with coordinates (X1,Z1). A line L1 is

8   perpendicular to the line between point P=(0,0) and the center (Xc,Yc) of the circular arc comprising

9   skeleton S intersecting the point P=(0,0). The value X2 represents the horizontal distance between

10   the points on line L1 and circular arc comprising skeleton S at coordinate Z2. In addition, it will

11   be appreciated that the origin of the XY plane, point P=(0,0) also resides on the circular arc, so that

12   the coordinates of three points on the circular arc comprising the skeleton S, along with the

13   coordinates of the center of the circle that includes the circular arc, will be known. Parameterizing

14   the arc S in this manner will have several advantages. First, if the locations Z1 and Z2 are relatively

15   far apart, depending on the radius R, the values X1 and X2 may also be relatively far apart. Second,

16   it would allow for use of a different road model, such as a parabolic arc, as will be described below.

17   Given a triplet (X1, X2,d), where "d" is the pitch (that is, the angle of the camera relative to

18   the Z axis) of the camera, and an image Ψ, it is desired to generate a warp of the image Ψ to a view

19   in which the roadway is essentially a straight line. It is possible to warp the image onto the XZ

20   plane, but instead the image is warped to the space R,β. Initially, given R, a and b, it should be

21   recognized that

22
$$R^2 = a^2 + b^2 \tag{1}$$

23   In addition

$$X = \left(R + \Delta R\right)\cos\!\left(\beta + \beta_0\right) \qquad (2)$$

1

2   and

3

$$Z = \left(R + \Delta R\right)\sin\left(\beta + \beta_0\right) \qquad (3)$$

4   where $\beta_0 = \tan^{-1}\!\left(\dfrac{a}{b}\right)$.

5   In addition, since, for a point $P(X,Y,Z)$ in three-dimensional space, the coordinates (x,y) of

6   the projection of the point in the image are given by

7

$$x = \frac{fX}{Z} \qquad (4)$$

8   and

9

$$y = \frac{fY}{Z} \qquad (5)$$

10   where X and Z are determined as above and Y is a function of the camera height Y_h, the pitch "d"

11   and the point's coordinate along the Z axis

12

$$Y = -Y_h + dZ \qquad (6).$$

1 In equation (6), Y_h is a positive value and is subtracted from "dZ" since the surface of the roadway

2 11 is below the camera 14. It will be appreciated that, at the point Z=0 directly below the camera,

3 $Y=Y_h$, as required.

4 Since

$$R^2 = \left(X_1 - a\right)^2 + \left(Z_1 - b\right)^2 \tag{7}$$

6 and

$$R^2 = \left(X_2 - a\right)^2 + \left(Z_2 - b\right)^2 \tag{8}$$

and given the relation in equation (1), solving for "a" and "b"

$$a = \frac{\left(X_2^2 + Z_2^2\right)Z_1 + \left(X_1^2 + Z_1^2\right)Z_2}{2\left(X_2 Z_1 + X_2 Z_2\right)} \tag{9}$$

and

$$b = \frac{X_1^2 + Z_1^2 - 2aX_1}{2Z_1} \tag{10}.$$

12 After values for "a" and "b," the "X" and "Z" components of the center of the circular arc S in the

13 XZ plane, the radius R can be determined using equation (1).

14 Using the values for "a" and "b" determined using equations (9) and (10), the value for the

15 radius R can be determined using equation (1). In addition, using equations (4) through (6) and the

16 coordinates (x,y) of each point in the image Ψ, the coordinates (X,Y,Z) of points in three-

17 dimensional space that are projected onto the image can be determined. Using the coordinates

1   (X,Y,Z), and the values for the radius R and β_0, the image can be warped from the (x,y) space to a

2   $\Delta R,\beta$ space using equations (2) and (3).

3   As noted above, the image Ψ in rectangular ((x,y)) coordinates can be warped to $\Delta R, \beta$ space.

4   At this point, it is desired to determine the range and resolution of those parameters. In one

5   embodiment, it is desired to have the resolution on the order of one-tenth meter by one-tenth meter.

6   Accordingly, it is desired to determine $\Delta\beta$ such that $\Delta\beta R$ is on the order of a predetermined length,

7   which, in one embodiment, is one-tenth meter.

8   The range is determined as follows. As noted above, warping the image of the roadway to

9   R,β space effectively provides a warped image Ψ' in which the roadway is straight, not curved. An

10 illustrative image is depicted in FIG. 3. As shown in FIG. 3, roadway 30 is divided into two regions,

11 including a near region 31 and a more distant region 32. In one embodiment, if the vertical

12 coordinates of the picture elements, or "pixels," that are subtended by the roadway in FIG. 3 extends

13 from -120 to -10, the vertical coordinates of the near region 31 extend from -120 to -20. In relating

14 the image in $\Delta\beta$,R space to the physical roadway in three-dimensional coordinates, it should be noted

15 that the bottom line of the warped image Ψ' maps to a line of width ΔX at distance Z, where

$$Z = \frac{fY}{y} \tag{11}$$

17 and, if, as shown in FIG. 3, the width of the image, with the horizontal coordinates extending from

18 -160 to 160 pixels, is 320

19
$$\Delta X = \frac{\Delta x Z}{f} = \frac{\Delta x f Y}{yf} = \frac{\Delta x Y}{y} = \frac{320 Y_h}{-120} \tag{12}$$

20 The range of R, which is taken to be ΔR, is $3\Delta X$.

21 In determining the range of β, it should be noted that Z_{max}, the maximum value of Z for the

22 roadway, is

1

$$Z_{max} = \frac{fY}{-10} \qquad (13).$$

2 Since

3
$$\sin\left(\beta_{max} + \beta_0\right) R = Z_{max} \qquad (14),$$

4 the value of β_{max} is

5
$$\beta_{max} = -\beta_0 + \sin^{-1}\left(\frac{Z_{max}}{R}\right) \qquad (15).$$

6 With this background, operations performed by processor 14 will be described in connection

7 with the flow chart in FIG. 4. Generally, the operations proceed in two phases. In the first phase,

8 the processor 14 performs a rough alignment using a straight road model. In that operation, the areas

9 of the image Ψ' are detected that appear to belong to road direction indicators, such as lane markings,

10 tire marks, edges and so forth. In the second phase, the rough alignment generated during the first

11 series of steps is used, along with information in the image Ψ' including both regions 31 and 32 to

12 determine a higher-order model. In that operation, only features found in the distant region 32 that

13 are extensions of features found in the near region 31 are utilized, which will ensure that non-

14 roadway features, such as automobiles, that may be found in the distant region 32 will be ignored.

15 Accordingly, and with reference to FIG. 4, the processor 14 initially receives an image Ψ

16 from the camera 14 (step 200). The image Ψ is a projection of points in rectangular three-

17 dimensional coordinates (X,Y,Z). After receiving the image Ψ, the processor 14 performs the first

18 series of steps in connection with the near region 31 (FIG. 3) of the roadway to generate a first-order

19 model of the roadway. Generally, for each of a predetermined number of selected values for X_1,

20 keeping predetermined values of the other parameters X_2 and radius R constant, the processor 14 will

21 generate a warped image Ψ', and generates a value for a cost function for each warped image Ψ'. The

1 value of the cost function will represent a measure of the number of vertical features that are present

2 in the warped image Ψ'. Since, for the warped image Ψ' for which the roadway appears to be

3 straightest, the number of vertical features that are present in the warped image Ψ' will be largest,

4 the processor 14 can select the value of the parameter X_1 that was used in generating the warped

5 image Ψ' associated with the largest cost function value as the appropriate value for parameter X_1.

6 Mores specifically, and with further reference to FIG. 4, after the processor 14 receives the

7 image Ψ, it will select one, "i-th," of the selected values for parameter X_1 (step 201) and using the

8 selected value and the predetermined values for parameters X_2 and R, generate a warped image Ψ'_i,

9 in which the image Ψ is warped to the R,β space (step 202). Thereafter, the processor 14 will

10 generate the cost function, as follows. The processor 14 initially generates a derivative image $d\Psi'$

11 along the horizontal ("x") coordinate of the image Ψ', the derivative representing the rate of change

12 of image brightness, or intensity, as a function of the horizontal coordinate (step 203). Thereafter,

13 to reduce the possibility that one extremely bright object might dominate, the processor 14 applies

14 a non-linear function, such as a binary threshold or sigmoid function, to the derivative image $d\Psi'$,

15 thereby to generate a normalized derivative image $n(d\Psi')$ (step 204). The processor 14, for each

16 column of pixels in the normalized derivative image $n(d\Psi')$ generated in step 204, generates a sum

17 of the pixel values of the pixels in the respective column (step 205), generates, for each column, the

18 square of the sum generated for the column (step 206) and forms a sum of the squares generated in

19 step 206 as the value of the cost function for the value of the parameter X_1 and the warped image Ψ'

20 generated therewith (step 207). In addition, the processor 14 determines, for each column, whether

21 the value of the square exceeds a selected threshold (step 208).

22 Following step 208, the processor 14 will determine whether it has performed steps 202

23 through 208 in connection with all of the selected values for parameter X_1 (step 209). If the

24 processor 14 makes a negative determination in connection with step 209, it will return to step 202

25 to select another value for parameter X_1 and performs steps 203 through 209 in connection therewith.

26 The processor 14 will perform steps 202 through 209 in connection with each of the selected

27 values for parameter X_1 to generate cost values therefor. When the processor 14 determines in step

-10-

1   209 that it has performed steps 202 through 209 in connection all of the selected values for parameter

2   X_1, it will sequence to step 209 to identify, among the cost function values generated in step 207,

3   the maximum cost function value (step 210). In addition, the parameter 14 will determine the value

4   of the parameter X_1 and the warped image Ψ' associated with the maximum cost function value

5   identified in step 209 (step 211). At this point the processor 14 will have completed the first phase,

6   with the warped image Ψ' comprising the rough alignment.

7   After completing the first phase, the processor 14 begins the second phase. In the second

8   phase, the processor 14 performs operations similar to those described above in the first phase,

9   except that

10   (a) it performs the operations in connection with pixels not only in the near region 31, but

11   also in the far region 32, and

12   (b) it generates the cost functions only in connection with columns that were determined in

13   step 208 to exceed the threshold

14   (step 212) to determine the values for the respective parameters.

15   The road skeleton S can also be modeled as a parabolic arc. In this case, it will be assumed

16   that the major axis of the parabolic arc is along the X axis in three-dimensional space, which, as

17   noted above, corresponds to the horizontal, or x, axis of the image Ψ. In that case, the road skeleton

18   will conform to the equation

19
$$X \;=\; aZ^2 + bZ + c \tag{16},$$

20   where coefficients "a," "b" and "c" are constants. The camera 14 is selected to be at the point

21    $(X,Z)=(0,0)$ on the skeleton S, in which case constant "c" is equal to zero. Lane markings are

22   essentially horizontal translations from the skeleton, and therefore they can be modeled using

23   equations of the same form as equation (16), and with the same values for coefficients "a" and "b" as

24   that in the equation for the skeleton S, but different values for coefficient "c." It will be appreciated

1 that the value for coefficient "c" in the equations for the lane markings will indicate the horizontal

2 displacement for the lane markings from the skeleton S for any point Z.

3 In the case of the parabolic arc model, the image Ψ can be warped to an image Ψ', in which

4 the skeleton is straight, as follows. If (x,y) are the coordinates of a point in image Ψ that is a

5 projection of a point with coordinates (X,Y,Z) in three-dimensional space

6

$$x = \frac{fX}{Z}$$

(17).

$$y = \frac{fY}{Z}$$

If a point in the image is a projection of a point the roadway,

$$Y = -Y_h + dZ$$

(18).

9 where, as above (see equation (6)), Y_h is the height of the camera off the roadway and "d" is the pitch

10 angle of the camera 14 relative to the horizontal axis Z. In equation (18), Y_h is a positive value, and

11 is subtracted from "dZ" since the surface of the roadway 11 is below the camera 14. It will be

12 appreciated that at the point Z=0 directly below the camera, $Y=Y_h$, as required. If values for "f," the

13 focal length of the camera 14, Y_h and d are known, it is possible to transform the coordinates (x,y)

14 of points in the image Ψ to the coordinates (X,Z) of points in three dimensional space, and vice

15 versa. The values of the parameters f and Y_h are known and the value of parameter d will be

16 determined in the course of determining values for coefficients "a" and "b" for the parabolic arc

17 model equation (16). Also, given the values of coefficients "a" and "b" in equation (16), an overhead

18 view (X,Z) of the skeleton of the roadway, that is, a view in the XZ plane, can be warped to a warped

19 view (C,Z) in which the skeleton S has the equation C=0. In that case, roadway markings, which,

1   as noted above, are also modeled as parabolic arcs, will have equations C=c, where "c" is the value

2   of the constant "c" in equation 16 for the respective roadway markings.

3   Accordingly, it is desired to determine the values of coefficients "a" and "b" and the pitch

4   angle "d" that, when used to warp the overhead view (X,Z) of the skeleton S to the overhead view

5   (C,Z), will result in a skeleton S that is a straight line. In that operation, a cost function is defined

6   for the view (C,Z) whose value will be a maximum for the correct values of "a," "b" and "d." As

7   with the methodology described above in connection with FIG. 4, searching for the maximum of the

8   cost function's value is performed in two general phases, with a near region being used in the first

9   phase, and a more extended region being used in the second phase. The value of the cost function

10   is determined as follows. Given assumed values for "a," "b" and "d," the image Ψ is warped to an

11   image Ψ'. The image Ψ is an image of the roadway (and possibly other objects and features) in

12   which the skeleton of the roadway is, in an overhead (X,Z) view, a parabolic arc. On the other hand,

13   image Ψ' is an image of the roadway (and possibly other objects and features) in which the skeleton

14   of the roadway may, in an overhead (C,Z) view, be a straight line, depending on the values for "a,"

15   "b" and "d" that were used in the warping. After the warped image Ψ' has been generated, the

16   warped image is projected onto the warped image's horizontal "x" axis by summing the pixel values

17   in the respective columns. The derivative of the sums across the warped image's horizontal "x" axis

18   is then determined, and a sum of the absolute values of the derivative across the warped image's

19   horizontal "x" axis is generated, with that sum being the value of the cost function. These operations

20   are repeated for a number of assumed values for "a," "b" and "d" to generate a number of cost

21   function values.

22   The value of cost function value will be larger if the projection onto the warped image's

23   horizontal projection is sharper, which will occur if there are more vertical features in the warped

24   image Ψ', and it would be possible to select the warped image Ψ' for which the cost function value

25   is greatest as the warped image Ψ' in which the skeleton S of the roadway appears as a straight line.

26   If there were no objects in the image Ψ, and hence warped image Ψ', other than the roadway 11, this

27   would be correct.

1   However, if there is clutter, such as other objects, in the image Ψ, and hence warped image

2   Ψ', with strong edges, the value of the cost function tends to get dominated by the clutter, which may

3   result in an improper warped image Ψ' being selected. The two-phase methodology reduces the

4   likelihood of this occurring. In the first phase, the image Ψ is warped to provide warped images Ψ'

5   using a straight road model, that is, with value of coefficient "a" set to zero and the values of "b" and

6   "d" may be zero or non-zero. In each warped image Ψ', areas that appear to belong to road direction

7   indicators, such as lane markings and tire tracks, as opposed to lines associated with other objects,

8   such as cares, are then identified. In addition, during the first phase, a preliminary value for

9   coefficient "b" and a value for pitch "d" are determined.

10   Thereafter, in the second phase, image Ψ is again warped, to generate warped images Ψ''_i,

11   using selected values "a_i" for coefficient "a" and the preliminary value for coefficient "b" and the

12   value for pitch "d" that were determined during the first phase. Using areas vertically higher in the

13   respective warped images, which represent areas in three-dimensional space (X,Y,Z) that are further

14   from the vehicle 10, the cost function values are generated, and an assessment as to the warped

15   image Ψ''_i for which the skeleton S most approximates a straight line. The value "a_i" that was used

16   in generating the warped image Ψ''_i for which the skeleton S most approximates a straight line is

17   selected as the value for coefficient "a" for the model represented by equation (16). The value pitch

18   "d" identified in the first phase is selected as the pitch "d." The value of coefficient "b" value for the

19   model represented by equation (16) corresponds to the value $\hat{b}$ which, as the coefficient of the linear

20   term in the parabolic model for which the value "a_i" is identified as the coefficient "a" in the

21   parabolic model, most approximates the straight line model, using the preliminary value for "b," that

22   was developed during the first phase.

23   More specifically, and with reference to the flow chart in FIG. 5, after the processor 14

24   receives an image Ψ (step 250), it will, in the first phase, select initial guess for the values for pitch

25   "d" and coefficient "b" (step 251) and, using those values, warp the image Ψ (step 252) thereby to

26   generate a warped image Ψ'. The processor 14 then, for each column of pixels in the warped image

27   Ψ', sums the pixel values for the pixels in the near region 31 in the column (step 253), generates

1 values representing the derivative in the horizontal direction (step 254) and generates values that

2 correspond to the absolute value of the derivative (step 255). It will be appreciated that portions of

3 the warped image Ψ' that contain, for example, edges or lane markings will produce peaks in the

4 absolute values generated in step 255, since the edges and lane markings will correspond to fast

5 transitions from dark-to-light or light- to-dark regions of the images. The processor 14 then

6 thresholds the absolute values generated in step 255 (step 256), that is, for any absolute value that

7 is less than a predetermined threshold value, the processor 14 sets the absolute value to zero. For

8 the absolute values that are above the threshold, the processor 14 then finds local maxima (step 257).

9 The local maxima, which will be identified as peaks "p_i" typically correspond to lane markings in

10 the warped image Ψ', although some peaks p_i may be caused by a strong edge that is not part of the

11 roadway, such as an automobile a short distance ahead of the vehicle 10.

12 After identifying the peaks p_i, the processor 14 searches for values for the coefficient "b" and

13 pitch "d" using a search methodology for each of the peaks p_i (step 258). In that operation, in each

14 of a series of iterations "j" (j=1,...,J), the processor 14 selects a value d_j for pitch d. In each iteration

15 "j," the processor 14, in each of a series of iterations "k" (k=1,...), selects a value b_k and performs

16 steps 252 through 257 in connection therewith to find values b_k^i for which the respective peaks p_i are

17 maximum. After completing the iterations "j" the set of points (d_j, b_k^i) in a (d,b) plane that are

18 associated with each peak p_i form a line l_i. The lines l_i that are associated with features along the

19 roadway, such as lane markings and tire tracks, will intersect at or near a point (d_x, b_x) in the (d,b)

20 plane, and the processor 14 will identify that point and determine the appropriate values for

21 coefficient "b" and pitch "d" as b_x and d_x, respectively. If there are any objects that are not associated

22 with features of the roadway 11, such as automobiles, in the near region 31 that are associated with

23 peaks p_i, lines l_i that are associated therewith will generally not be near point (d_x, b_x) and will be

24 ignored. In addition, it will be appreciated that, since the lines l_i that are at or near point (d_x, b_x) are

25 associated with features along the roadway, and the processor 14 can readily determine which

26 columns in the warped image Ψ' contain those features. This, along with the values of coefficient

27 "b" and pitch "d" will be used in the second phase.

1   In the second phase, the processor 14 determines a value for coefficient "a" using regions of

2   the image including both the near region 31 and the far region 32, generally emphasizing columns

3   that are associated with or near the subset of peaks p_i that it identified as being associated with

4   features of the roadway. In the second phase, the processor 14 initially selects a plurality of values

5   a_i (step 260) and, for each value a_i, generates an adjusted value $\hat{b}_i$ so that the line $X = b_x Z + c$

6   (where b_x corresponds to b_x determined in the first phase) best approximates the curve

7    $X = a_i Z^2 + \hat{b}_i Z + c$ with the value of "c" being set to zero (reference equation 16) over a range

8   of "Z" as determined in the first phase (step 261). Thereafter, the processor 14 selects a value of "a_i"

9   (step 262) and warps the original image Ψ to generate a warped image Ψ''_i using the values "a_i" and

10   "b_x" as coefficients "a" and "$\hat{b}_i$ and value d_x as the pitch "d" (step 263). The processor 14 then

11   projects a portion of the warped image Ψ''_i, specifically the portion in the far region 32, onto the

12   warped image's horizontal axis by summing the pixel values of the pixels in each column in that

13   region (step 264) and then generates the derivative of the sums along the horizontal axis (step 265).

14   For columns that are associated with peaks p_i that the processor 14 had determined in the first phase

15   were associated with features of the roadway 11, such as lane markings and tire tracks, the processor

16   14 will generate the absolute value of the derivative (step 266) and generate a value corresponding

17   to the sum of the absolute values (step 267). It will be appreciated that, by performing steps 266 and

18   267 in connection only with columns that were determined in the first phase to be associated with

19   features of the roadway 11, the processor 14 will minimize contributions due to features that are not

20   associated with the roadway, such as automobiles, which may otherwise unduly influence the result.

21   After performing steps 262 through 267 for the value "a_i" that was selected in step 262, the

22   processor 14 will determine whether it has selected all of the values "a_i" that were selected in step

23   260 (step 268), and, if not, return to step 262 to select another value "a_i" and perform steps 263

24   through 267 in connection therewith. The processor will perform steps 262 through 267 through a

25   plurality of iterations until it has generated the sum of the absolute value of the derivative for all of

26   the values "a_i" that were selected in step 260. When the processor 14 determines in step 268 that it

1 has selected all of the values "a_i" that were selected in 260, it will have generated a sum of the

2 absolute value of the derivative for all of the values "a_i," in which case it will sequence to step 269.

3 In step 269, the processor identifies the value "a_i" for which the sum is the largest (step 269). The

4 correct parameters for the skeleton S are, as the value of coefficient "a," the value a_i that was selected

5 in step 269, as the value of coefficient "b," the value of $\hat{b}$ that was generated for that value "a_i" in

6 step 261, and, as the pitch "d," the value d_x generated in the first phase.

7 The invention provides a number of advantages. In particular, the invention provides a

8 system for estimating the skeleton S of a roadway 11 for some distance ahead of a vehicle. Two

9 specific methodologies are described, one methodology using a model in which the roadway is

10 modeled as a circular arc, and the other methodology using a model in which the roadway is

11 modeled as a parabolic arc, in both methodologies requiring only one image, although it will be

12 appreciated that the system can make use of a combination of these methodologies, and/or other

13 methodologies. Determining the skeleton of a roadway for some distance ahead of a vehicle can be

14 useful in connection with autonomous or assisted driving of the vehicle.

15 It will be appreciated that a system in accordance with the invention can be constructed in

16 whole or in part from special purpose hardware or a general purpose computer system, or any

17 combination thereof, any portion of which may be controlled by a suitable program. Any program

18 may in whole or in part comprise part of or be stored on the system in a conventional manner, or it

19 may in whole or in part be provided in to the system over a network or other mechanism for

20 transferring information in a conventional manner. In addition, it will be appreciated that the system

21 may be operated and/or otherwise controlled by means of information provided by an operator using

22 operator input elements (not shown) which may be connected directly to the system or which may

23 transfer the information to the system over a network or other mechanism for transferring

24 information in a conventional manner.

25 The foregoing description has been limited to a specific embodiment of this invention. It will

26 be apparent, however, that various variations and modifications may be made to the invention, with

27 the attainment of some or all of the advantages of the invention. It is the object of the appended

1   claims to cover these and such other variations and modifications as come within the true spirit and

2   scope of the invention.

3   What is claimed as new and desired to be secured by Letters Patent of the United States is: